

System efficiency prediction of a 1kW capacity grid-tied photovoltaic inverter

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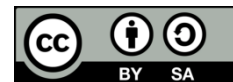
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ABSTRACT

This article presents the system design and prediction performance of a 1kW capacity grid-tied photovoltaic inverter applicable for low or medium-voltage electrical distribution networks. System parameters, for instance, the longitude and latitude of the solar plant location, panel orientation, tilt and azimuth angle calculation, feasibility testing, optimal sizing of installment are analyzed in the model and the utility is simulated precisely to construct an efficient solar power plant for residential applications. In this paper, meteorological data are computed to discuss the impact of environmental variables. As regards ensuring reliability and sustenance, a simulation model of the system of interest is tested in the PVsyst software package. Simulation results yield that the optimum energy injected to the national grid from the solar plant, specific production, and performance ratio are 1676kWh/year, 1552kWh/kWp/year, and 79.29% respectively. Moreover, the predicted carbon footprint reduction is 23.467 tons during the 30 years lifetime of the system. Therefore, the performance assessments affirm the effectiveness of the proposed research.

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1. INTRODUCTION

In this modern civilized world, the requirement of electrical energy is inevitable. This era conforms to rapid growth and augmentation of the industrial sector and modernization of technical premises, which revolutionize the human lifestyle. This sophisticated tech-savvy global reformation is predominantly responsible for the increasing demand for electrical energy. However, to date, the conventional method of electricity generation depends on burning fossil fuels such as natural gas, coal, oil, which produce tons of carbon dioxide as by-products that are not only life-threatening for human civilization but also can endanger the natural ecosystem. Moreover, the amount of this kind of natural resource (gas, coal, oil) is limited and is decreasing drastically due to meet up the increased load demand [1]-[3]. The US energy information administration warned that in 2025 with a yearly increment rate of 2.35%, the worldwide energy consumption rate will be 24.673TWh [4]. To deal with these issues like ensuring energy security, system reliability, and durability, producing energy from renewable sources is considered as an environmentally friendly solution and also, a resource that can provide continual and clean energy access. Some of the renewable energy sources include solar power, tidal and ocean wave energy, wind power, biogas, biomass, and hydropower system. However, it is reported that the solar energy available for the earth is equivalent to

104 times (1.2×10^5 TW) of its current production and operation rate [5]. Therefore, it can be implied that the most prominent and sustainable energy resource is solar power as an intriguing renewable solution.

The penetration of renewable energy sources into the modern power system infrastructure for substantial and efficacious energy routing yields implications of scalable, controllable, and effective power management interfaces such as power electronic converters, communication networks, and associated control units. In this regard, practitioners and researchers indulge themselves in designing and implementing novel architectures of renewable energy solutions, which can be deployed for industrial and residential applications [6]-[13]. Since DC loads are prevalent in microgrids and smart power distribution systems, conversion between AC and DC or a combination of both AC and DC is significant. Besides, where the national grid requires AC power generation and integration, a renewable resource like solar power provides DC energy conversely. To harness this solar energy into reusable DC power, a solar photovoltaic module is required. Besides, to convert this DC into AC power, two types of system topology are considered-standalone (islanded mode) and grid-tied (grid-connected mode). Between these two, the grid-tied photovoltaic system is the most lucrative one for business and economic entities. In this system, during day time the electrical appliances are run by solar energy. The surplus energy produced during day time is directly fed to the national grid. On the other hand, during the night time due to the absence of solar energy access, the consumers can procure the required amount of energy from the grid authority. As this grid-tied system needs no energy storage like a battery bank or supercapacitor, the charge controller ensures clean electricity production and injection into the grid without any transmission and distribution losses [14]-[16].

Design and establishment of a solar energy-based power plant infer several constraints and variables such as longitude, latitude, orientation, inclination, feasibility test, and sizing, which ought to be optimized through simulations. Additionally, recurrent and extensive performance evaluations are mandatory for estimating overall system efficiency under different operating conditions. Thereby, in this article, a research framework that predicts the power efficiency of a 1kW capacity grid-tied photovoltaic inverter is presented. The prediction is carried out employing PVsyst, which is a modeling tool equipped with all the required facilities along with detailed meteorological data for which the researchers and the engineers can rely on its simulated output [17]-[18].

Some state-of-the-art prediction methodologies have been applied in solar photovoltaic systems recently. In [19], new real-time prediction models for output power and energy efficiency are reported, which have been confirmed using yearly and monthly average measurements of a grid-connected solar power system in Macau. In this paper, the online efficiency prediction model was developed by taking into account the ratio of the predicted output power to the anticipated solar irradiance. In [20], a novel technique for modeling and forecasting the performance of a standalone solar power system demonstrated wherein algebraic simultaneous calculations of the design parameters have been calculated for a simplified testbed. However, this framework has not been validated for grid integration. The research documented in [21] describes a detailed comparison of performance-model estimations within the solar advisor model (SAM) developed by the US department of energy to determining PV system performance to evaluate the efficacy of predicting energy production. In this work, the inputs of the models are the recorded measurements of meteorological and irradiance data from co-located photovoltaic arrays. Another robust performance predictor of a 20kWp grid-connected photovoltaic plant is proposed in [22], where two artificial neural networks (ANN) models have been employed for analyzing experimental climate and electrical data. In the demonstration, the first model is a multivariate one based on the solar irradiance values and air temperature, whereas the second univariate model takes solar irradiance data as inputs. However, from the literature reviews of the photovoltaic power plant models and related prediction methodologies, this paper presents a comparatively simple yet reliable application of a custom performance estimation platform, referred to as PVsyst, to project efficiency profiles of a localized 1kW solar facility taking into account the area-specific information. The major contribution of the articulated research is analyzing a grid-tied photovoltaic inverter to develop a predictor of the system efficiency considering meteorological data recorded for a certain period. The remainder of the manuscript arranged as follows. Section 2 presents the overview of the proposed system. In the follow-up, Section 3 elaborates the meteorological characteristics of the location of interest. Then, Section 4 subsumes the specifications to run tests. Section 5 presents the simulation results of the photovoltaic model and finally, Section 6 concludes the article.

2. PROPOSED SYSTEM TOPOLOGY

A grid integrated photovoltaic inverter is analyzed in this paper to develop a predictor that can estimate the system efficiency. Figure 1 presents the brief functional diagram of the system topology. Here, the input DC power from the solar photovoltaic (PV) modules fed to the grid-tied inverter (GTI). The converted AC output power of GTI is then delivered to a residential facility via the bidirectional metering

interface, which is indicated here as a net meter. This bidirectional net meter ensures the process of supplying the excess electricity produced from the solar PV modules injected into the national grid. Therefore, the electricity bill is calculated based on the energy recorded in the net meter. The solar energy meter reads the total power generation from the PV modules and the consumption meter is responsible for reading the overall power consumed by the residential unit. If the amount of electricity generated and disbursed from the rooftop PV modules is higher than the imported power from the national grid, the utility authority pays for this power in kWh [23].

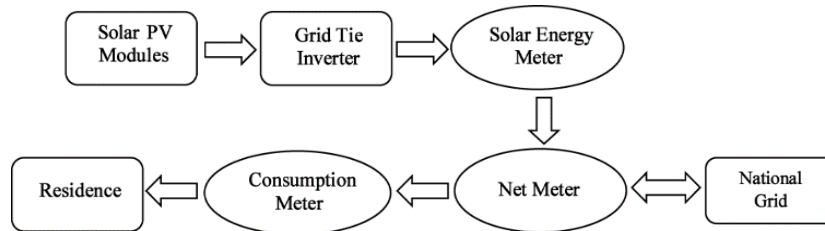


Figure 1. Functional diagram of the proposed system

Table 1. Monthly Meteorological Values

Month	Global Irradiation (kWh/m ² /day)	Diffuse Irradiation (kWh/m ² /day)	Temperature (°C)	Wind Velocity (m/s)
January	4.21	1.57	17.5	0.40
February	4.66	2.09	20.9	0.60
March	5.73	2.39	25.1	0.89
April	5.92	2.78	27.3	1.30
May	5.73	3.25	28.0	0.99
June	4.96	3.07	27.6	1.10
July	4.92	3.06	28.0	1.21
August	4.55	2.93	28.3	0.99
September	4.86	2.82	27.5	0.70
October	4.52	2.42	26.6	0.49
November	4.63	1.45	22.7	0.30
December	4.21	1.23	19.0	0.20

3. METEOROLOGICAL CHARACTERISTICS OF THE PLANT LOCATION

This paper considers a solar power facility located in a specific area with particular geographical and meteorological properties. Space, where the plant of interest installed for the research endeavor, is in Swamibag, Dhaka 1100, Bangladesh with a location map-latitude: 23.72° north, longitude: 90.42° east, and altitude: 4 m the standard sea level.

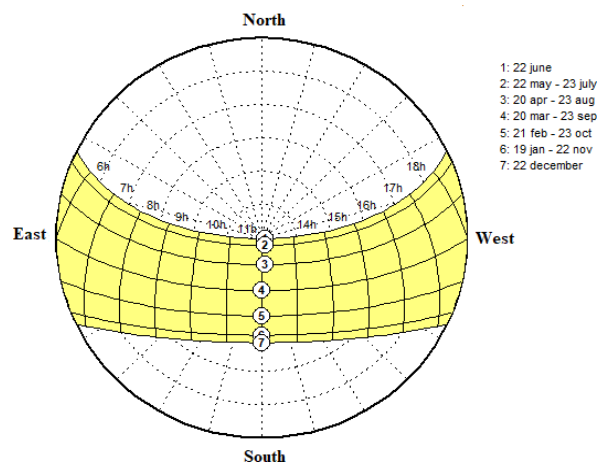


Figure 2. Solar path diagram of Swamibag, Dhaka 1100, Bangladesh

The meteorological information such as the horizontal global irradiation, horizontal diffuse irradiation, ambient temperature, and wind velocity of the plant location was recorded from the year 1981 to 2010 applying a software package, named Meteonorm (version 7.1). Table 1 enlists the monthly meteorological information. From the presented values, it can be implied that the annual average global and diffuse irradiances are $4.91\text{kWh}/\text{m}^2/\text{day}$ and $2.42\text{kWh}/\text{m}^2/\text{day}$, respectively, provided that the average temperature and wind velocity are 24.9°C and 0.8m/s , respectively. Also, for more precise speculation of the plant's solar power access, the solar path diagram in the polar coordinate form of the site is illustrated in Figure 2. From this figure, it can be declared that at noon, the sun faces directly to the south direction in all scenarios.

4. SYSTEM SPECIFICATIONS

In this paper, system efficiency is predicted of a 1kW capacity grid-connected PV inverter that is planted in a specific geographical location for supplying electricity to a residential unit. In this regard, calculation of energy demand of a residence, optimization of tilt and azimuth angles of the installed plant, specifications of the PV modules, and grid-tied inverter documented in the following subsections.

4.1. Demand calculation

As a standard, the roof-top of a 1200 square feet apartment in the proposed location has been selected for the electricity demand calculation. Table 2 shows the monthly consumption rate (kWh) of the facility. From this table, it can be observed that the annual consumption rate can be approximated as 1708kWh. Based on these data, the average consumption per day has calculated as 4.6794kWh . Dividing the average consumption per day by the equivalent solar hour, the power required from the solar PV panel has been determined as 1.1kW. The equivalent solar hour considered here is 4.65 [24].

Table 2. Month-wise consumption rate

Month	Consumption (kWh)	Month	Consumption (kWh)
January	86	July	122
February	95	August	195
March	73	September	177
April	70	October	221
May	158	November	175
June	200	December	136

4.2. Tilt and azimuth angle optimization

By applying the PVsyst software's tilt and azimuth angle optimization technique for yearly irradiation yield, the projected annual meteorological data for different tilt and azimuth angles in the case of a fixed titled plane are shown in Table 3. From this table, it can be depicted that by considering the tilt angle as 30° and azimuth angle as 0° for the projected location, the maximum annual irradiation of $1962\text{kWh}/\text{m}^2$ can be obtained. In this regard, rigorous arithmetical analysis for calculating the optimum orientation of solar PV panels described in [25] proclaiming that the optimized tilt and azimuth angle for Dhaka, Bangladesh are 30° and 0° respectively. This information corroborates the PVsyst software's simulated outcome. Figure 3 presents the optimized tilt and azimuth angle of the solar PV panel for the location of interest.

Table 3. Optimization of the annual irradiation data

Tilt Angle ($^\circ$)	Azimuth ($^\circ$)	Irradiation (kWh/m^2)
90	0	1171
30	180	1332
30	120	1535
30	90	1695
60	0	1729
0	0	1792
30	60	1833
30	0	1962

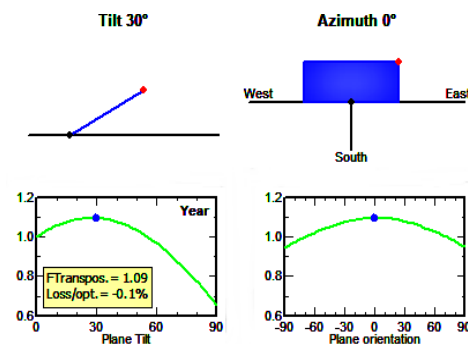


Figure 3. Optimized tilt and azimuth angle of the solar photovoltaic plane

4.3. PV module specifications

As a PV module, the Si-mono LG270S1C-B3 solar mono-crystalline panel with a maximum power output capability of 270Wp has been chosen for optimal sizing. In the PV array, there are 4 modules connected in series that render the array global power (nominal) as 1080Wp. Table 4 shows the specifications of the PV array. Figure 4 illustrates the I-V characteristic curve of the selected PV model under the standard testing condition (STC) (temperature 25°C and irradiance 1000W/m²). Besides, Figure 5 and Figure 6 present the effect of irradiance and temperature variations on the P-V characteristics of the PV module.

Table 4. Considered PV array specifications

Criterion	Specification
Model	Si-mono (LG 270 S1C-B3)
Number of modules	4
Unit nominal power	270 Wp
Rated power at operating condition (50°C)	968 Wp
Array operating voltage & current (at 50°C)	$V_{mpp} = 111 \text{ V}$ & $I_{mpp} = 8.7 \text{ A}$
Array operating voltage & current (at -10°C)	$V_{oc} = 172 \text{ V}$ & $I_{sc} = 9.2 \text{ A}$
Total cross-sectional area	6.6 m ²
Thermal loss factor	20.0 W/m ² K
Wiring ohmic loss fraction	1.5% at STC

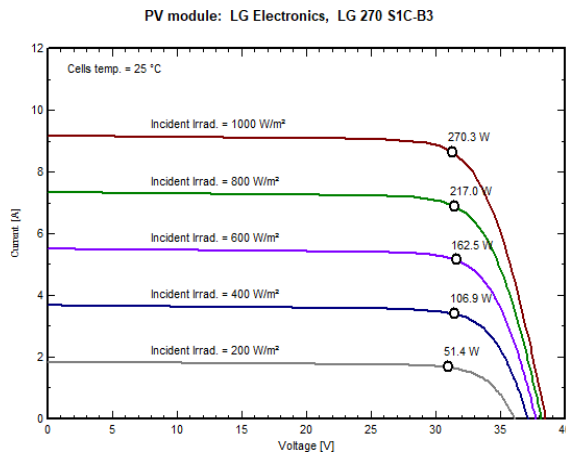


Figure 4. I-V characteristic curve

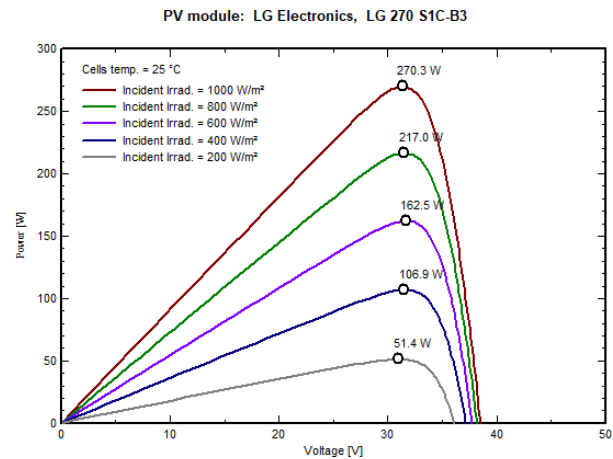


Figure 5. P-V characteristic curve subject to irradiance changes

4.4. Inverter model specifications

The UNO-DM-1.2-TL-PLUS single phase inverter model, manufactured by ABB, has been selected for deployment in this work. Optimal sizing has been accomplished with a maximum power output capability of 1.2kW AC, a maximum efficiency of 94.80% where the input operating voltage ranges between 90V to 580V DC and the output AC (RMS) voltage can be obtained as 230V of 50Hz frequency [26]. Table 5 shows the specifications of the inverter model, whereas Figure 7 illustrates the efficiency curve for 25°C.

Table 5. Grid tied inverter specifications for a single unit

Criterion	Specification
Model	UNO-DM-1.2-TL-PLUS (ABB)
Operating Input & Output Voltage	90-580 V DC & 230 V AC (rms)
Nominal Frequency	50 Hz
Nominal Power	1.20 kW _{ac}
Rated Power Factor	0.90 (Lagging)
Maximum Efficiency	94.80%

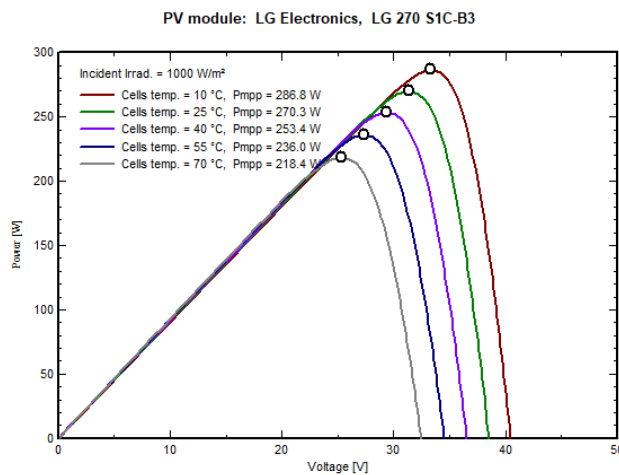


Figure 6. P-V characteristic curve subject to temperature changes

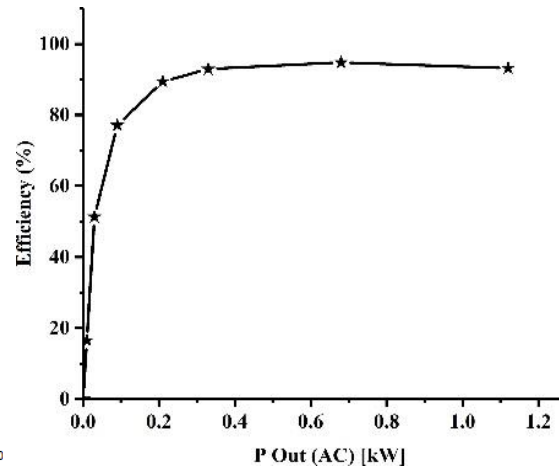


Figure 7. Efficiency curve of the selected grid tied inverter model

5. RESULT AND ANALYSIS

The overall performance analysis of the proposed 1 kW capacity grid-tied PV inverter is described in detail in the subsections.

5.1. Balances and primary results of the 1 kW system

Table 6 presents the summarized balances and the key outcomes of the designed project. It clearly states that yearly, the rate of horizontal global irradiation (*GlobHor*) is 1791.6 kWh/m², horizontal diffuse irradiation (*Diff Hor*) is 884.3 kWh/m², ambient temperature (*T_{Amb}*) is 24.88°C, global incident (*GlobInc*) radiation in collector plane is 1956.8 kWh/m², effective energy (*E_{Array}*) at the output of the array is 1805.3 kWh, energy injected into the grid (*E_{Grid}*) is 1675.6 kWh along with the performance ratio (PR) is 79.29%.

Table 6. Summarized balances and key outcomes of the proposed work

Month	GlobHor kWh/m ²	DiffHor kWh/m ²	T _{Amb} °C	GlobInc kWh/m ²	GlobEff kWh/m ²	E _{Array} kWh	E _{Grid} kWh	PR
January	130.4	48.7	17.47	178.2	174.1	169.2	158.6	0.824
February	130.4	58.4	20.87	159.4	155.5	148.7	139.0	0.808
March	177.7	74.0	25.14	196.5	191.2	178.0	166.2	0.783
April	177.7	83.4	27.29	175.3	169.9	158.4	146.9	0.776
May	177.7	100.7	27.98	160.2	154.4	146.7	135.5	0.783
June	148.8	92.1	27.55	130.5	125.5	120.8	110.3	0.782
July	152.6	95.0	28.04	135.2	130.1	124.9	114.1	0.781
August	141.1	90.7	28.25	133.6	128.9	123.0	112.2	0.778
September	145.9	84.6	27.47	150.5	145.7	138.4	128.0	0.788
October	140.0	75.1	26.60	161.0	156.6	148.1	137.6	0.791
November	138.9	43.6	22.70	187.7	183.6	172.4	161.7	0.797
December	130.4	38.0	19.02	188.7	184.7	176.7	165.6	0.813
Year	1791.6	884.3	24.88	1956.8	1900.3	1805.3	1675.6	0.793

5.2. Performance ratio

Performance ratio (PR) is defined as the ratio between the useful energy produced by the proposed system (*Y_f*) and the perfect system which would generate the energy (*Y_r*) continuously operated under standard test conditions (STC). On top of that, this PR calculation includes system losses and PV array losses. The system loss counted for the determination of inverter efficiency. Besides, the array losses include PV module efficiency, wiring loss, PV module quality, etcetera. The month-wise PR ratio deviation for the proposed system is presented in Figure 8. As the PR for 270W PV panel is 79.29%, it indicates that 20.71% of the total energy produced by the solar PV panel is not supplied to the load-end and can be considered wasted energy [27].

5.3. Normalized production

Figure 9 illustrates the normalized energy production rate in case of per installed kWp. Besides it implies that the produced useful energy supplied to the prosumer (Y_f) is 4.25 kWh/kWp/day, the PV array loss L_c is 0.78kWh/kWp/day, system loss (inverter loss) L_s is 0.33kWh/kWp/day.

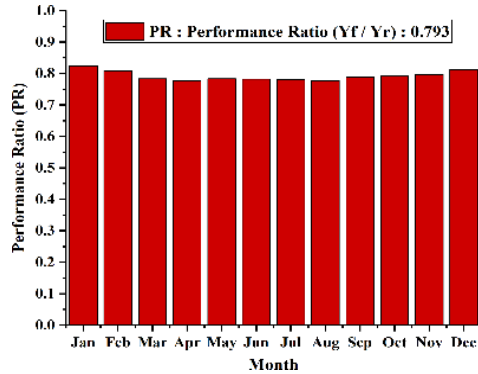


Figure 8. Performance ratio of the proposed system

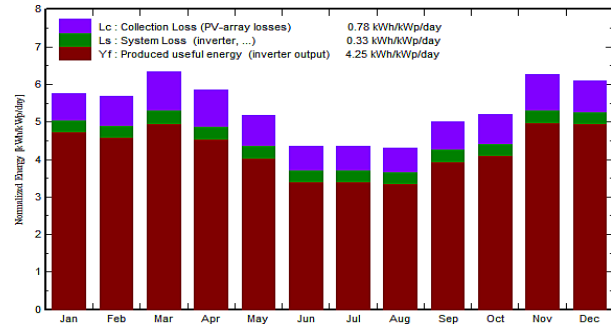


Figure 9. Normalized production rate of the proposed system

5.4. Loss diagram

Figure 10 depicts the loss diagram of the proposed system for the entire year. It clearly states that the highest amount of loss (11.3%) occurs for PV loss due to temperature. Besides, the inverter loss accounts for a 7.2% loss. Moreover, the effective irradiance on collectors is 1900kWh/m², and global horizontal irradiation is 1792kWh/m². Finally, the energy injected into the grid is 1676kWh with a PV conversion efficiency of 16.48%.

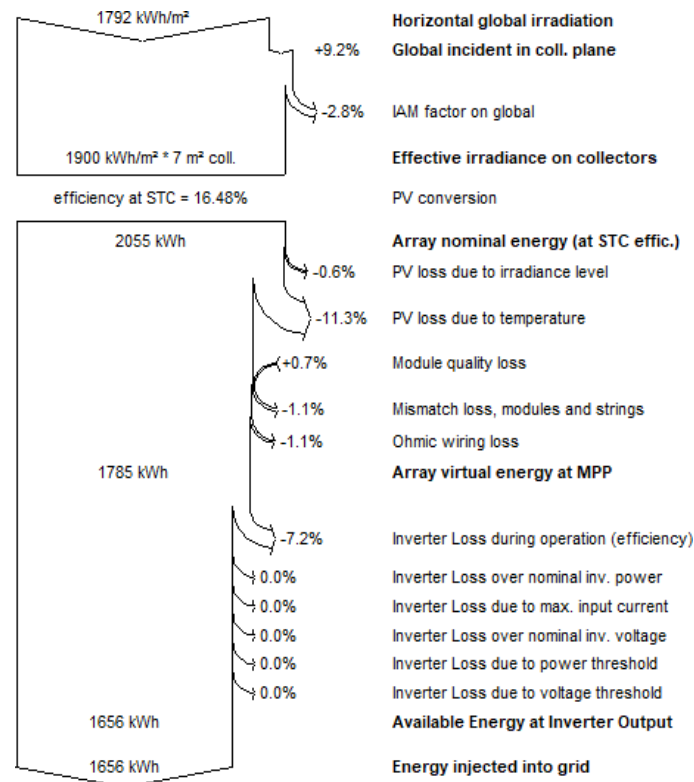


Figure 10. Loss diagram over the year

5.5 Carbon footprint reduction

For a pollution-free world and environment-friendly energy solutions, a global concept called carbon footprint reduction has come into play. The total production of greenhouse gases either by human activities or any other means represented by its equivalent tons of carbon dioxide (CO₂). Figure 11 ensures reduction of 23.467 tons of CO₂ emission for the next 30 years by installing the proposed 1kW capacity grid-tied photovoltaic inverter system.

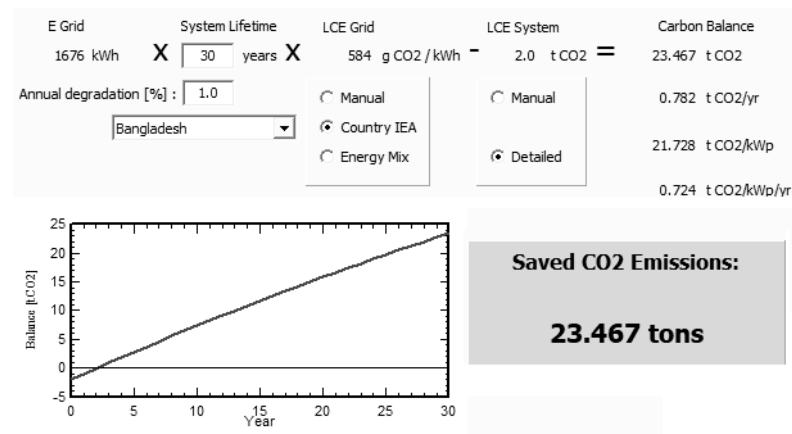


Figure 11. Carbon footprint reduction rate

6. CONCLUSION

In this paper, a detailed analysis and efficiency prediction of a 1kW capacity grid-tied photovoltaic inverter for a residential facility are reported. The simulated results suggest that this proposed system is responsible for the production of 1676kWh energy per year injected into the national grid. Moreover, it depicts that in March, the maximum amount of energy of 166.2kWh could be supplied to the national grid, whereas the least amount of energy that could be injected in June is 110.3kWh. Additionally, for a specific plant location in Bangladesh, the simulated performance ratio is 79.29%. Finally, the carbon footprint reduction of 23.467 tons CO₂ underscores the environmental friendliness of the presented system which can be a sustainable electricity supply authority for the prosumers.

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